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MODELLING SUPERCRITICAL FLOW-INDUCED SCOUR AROUND STRUCTURES

Sanaz. Mehrzad[1] , Colin D. Rennie[2], Ioan Nistor[3]
[1.]PhD Student, University of Ottawa, Canada
[2,3.] Professor, University of Ottawa, Canada
[4] rmehr026@uottawa.ca

Abstract: The present study investigates the scour mechanism and vortex structure around a square structure due to inland-propagating tsunami-like bores on a dry or flooded horizontal mobile bed. A series of hydraulic bores were simulated using a dam-break wave generated by the release of water impounded behind a rapidly-opening swing gate. A novel video-recording system was used to monitor the evolution of the scour and vortex structure. Image processing allowed tracking the time and spatial evolution of the scour and the observation of sediment movement around the structure. It was found that the scour mechanism associated with dam break waves differs from that of a steady flow. The influence of bed condition (fixed versus mobile) and (dry versus wet) on bore characteristics, and how they might affect the scouring process will be presented and discussed.

1 INTRODUCTION AND RESEARCH NEEDS

Field evidence indicates that destructive tsunamis cause substantial coastal sediment mobilization (Chen et al, 2016). Measurements collected from multiple tsunami events, such as the 1992 Nicaragua Tsunami and the 2004 Indian Ocean Tsunami, have recorded substantial evidence of scour around damaged buildings and bridge foundations (Yeh and Li, 2008). The field surveys noted that scouring was one of the primary causes of coastal structural damage (Chen et al, 2016).Tsunami waves have been observed with wave heights of 5–10 m. The inundating waves will be inevitably accompanied by very high flow velocities when they penetrate inland. The high flow velocities produce high bed shear stresses and large amounts of sediment movement over large areas, resulting in substantial beach erosion and scouring around a large number of structures (Li et al, 2012). Yeh and Li (2008) observed local scour at the seaward corner of a schoolhouse in Kalapakkom, India. The inundation depth was 0.95 m above the building's floor and the run up height was 4.1 m. The scour depth was approximately 1.5 m with a horizontal span of 5 m. They also observed an undermined patio in Devanaanpattinam, India, where the observed runup height was 3.0 m. The undermining resulted from swift channelized flows during the drawdown of the tsunami wave. During the 1993 Okushiri Tsunami attack, at the entrance of Okushiri Port, Japan, a scour depth of 4 m was created between breakwaters, causing the breakwater to overturn as a result of foundation failure. Generally, the first tsunami wave propagates over dry lands (dry bed condition) while the subsequent waves may intrude on the flooded coastline (wet bed condition) before full recession of the first wave. Previous research have shown that the water layer presence on the bed could influence the tsunami bore characteristics (Stansby et al 1998; Douglas and Nistor 2014). Laboratory experiments related to scour around structures caused by tsunamis are limited. Tonkin et al (2003) examined scour around a cylindrical structure located on a sloped wet sandy beach. Nakamura et al (2008) focused on scour around a square structure located on a horizontal wet sand bed. Both studies underline that such a tsunami-induced scour hole, occurring in such transient flow conditions, exhibited significantly different mechanisms than observed in steady current and consistent short-wave field studies. Laboratory waves employed in these studies were either solitary waves or long waves. At present, general scientific consensus indicates that solitary waves tend to be less representative of actual tsunamis due to their short period. This is particularly important for studies focusing on scour, where flow duration is a critical variable. The use of hydraulic bores generated from dam break waves have been shown to better replicate the temporal features of tsunami-induced flooding (Chanson. 2006). Using dam-break flow conditions, this study investigated the scour mechanism and vortex structure around the square structure due to inland-propagating tsunami bores on a dry and flooded horizontal bed. Additionally, characteristics of the bore, including run up, stream-wise velocity and bore front velocity for different initial downstream conditions (dry bed vs wet bed) will be presented.

2 EXPERIMENTAL SET UP

2.1 Flume and instrumentation

The hydrodynamic boundary conditions for these experiments were simulated using a dam-break method in a flume located in Hydraulics Laboratory at the University of Ottawa (Canada). The flume was 30 m long, 1.5 m wide and 0.8 m deep. The dam-break wave was generated by releasing water impounded behind a rapidly-opening swinging gate which was equipped with a lock and release mechanism. The sediment bed section was 3.30 m long and 1.5 m wide, delimited at each end by false floors as shown in Figure 1.

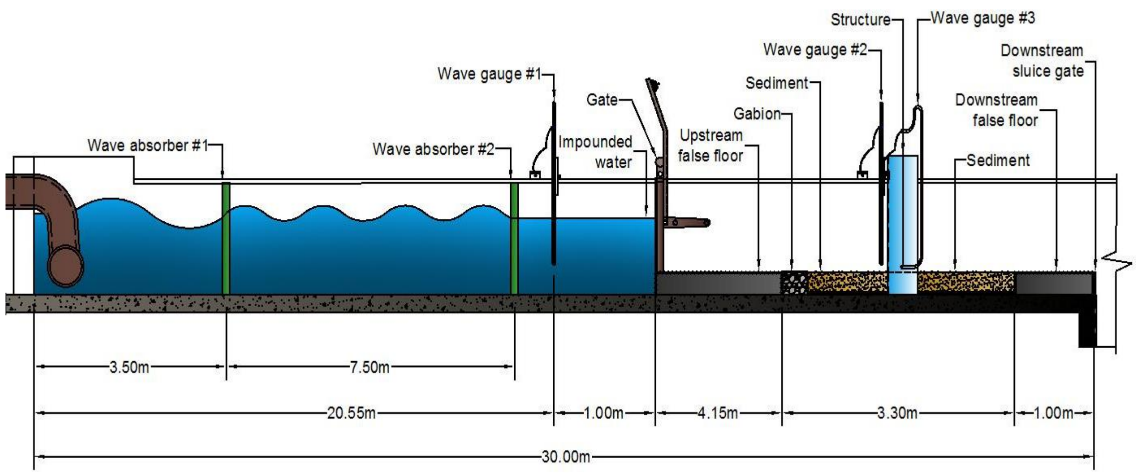


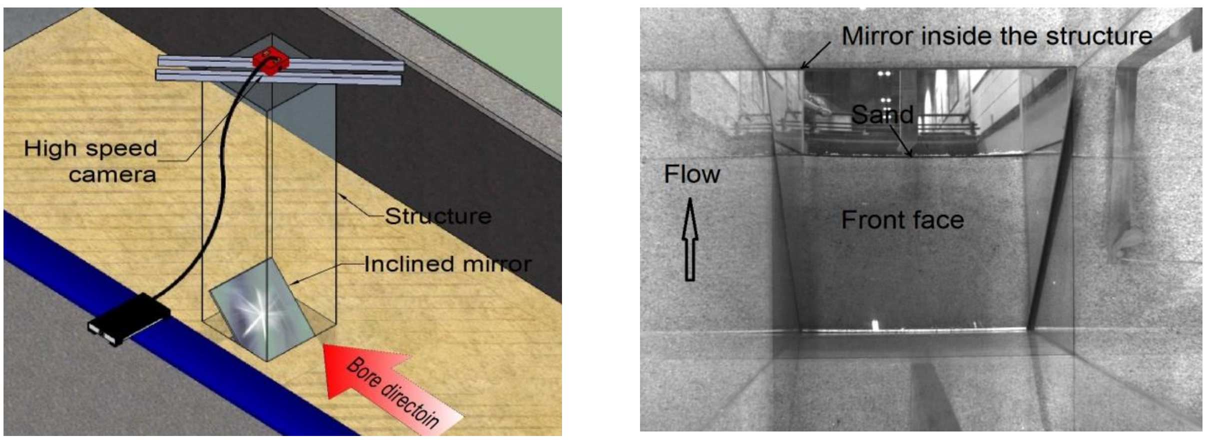
Figure 1: (a) Experiment setup, side view, (not to scale)

Two aluminum false floors with a height of 0.2 m were installed before and after the sediment bed, downstream of the gate, to provide formwork for the sediment section. A sluice gate was installed at the end of the downstream false floor to be able to create a wet bed initial condition. The upstream and downstream false floor had a length of 4.15 m and 1 m, respectively. The upstream false floor was covered with a layer of glued sand with a uniform grain size of 1 mm, in order to provide surface roughness, limiting the influence of the transition between the fixed and moveable bed. A grid system of 20 x 20 cm spacing was also painted on the top surface of the upstream false floor for measurement purposes.

The base of the sediment bed was composed of a layer of 1 cm thick coarse gravel covered by a geotextile sheet. The base layer drained water that infiltrated from below the false floor, to prevent the water from influencing the sediment bed. The sediment section was filled with 1 mm uniform sand. Directly downstream of the false floor, a 15 cm wide gabion was installed across the flume. The gabion was constructed with a wire box filled with coarse gravel, approximately 3 cm thick. The gabion was used to minimize the inevitable local scour that would occur at the interface of false floor and sediment section.

Three wave absorbers were installed in order to attenuate secondary waves within the reservoir and prevent reflective waves-induced in water level fluctuation at the test section.

Three WG-50 capacitance type wave gauges with an accuracy of 0.4% were used to record the time-history of the water surface elevation at different locations, using a sampling rate of 30 Hz. Two wave gauges were positioned as follows: one on the front face and the other one on the side face of the structure. The third wave gauge was placed at a distance of 1.0 m behind the swing gate, inside the reservoir. This wave gauge was used to record the time-history of the water surface elevation within the reservoir over the duration of the test. Two video cameras, a GoPro Hero™ Black and an IO Industrial Flare™ high speed video camera, were used during the experimental investigations a) to track the bore front as it propagated downstream towards the structure, and b) to record the evolution the of scour and vortex structure. A 0.2 m x 0.2 m square structure built of Plexiglas was used in the experiment. The structure was installed in the center of the sediment section. The square structure was transparent to allow for monitoring the scouring process by means of the high speed camera which was placed at the top of the structure. The monitoring of the scour was achieved with the help of a mirror inclined at 45° inside the structure as shown in Figure 2.



a) b)

Figure 2: (a) Experiment setup to monitor the scour process; (b) Reflected (looking from above-mirror inside) view of the structure's front face.

Turbulent velocity measurements were conducted with an Acoustic Doppler Velocimetry (ADV) using the Nortek Vectrino with a side-looking head equipped with four receivers using a sampling rate of 25 Hz (installed at x = 5.15 m from the gate).

2.2 Experimental Procedure

Before each experiment, the sediment bed was levelled and the reservoir was filled with water to the desired impounded water depth. The swinging gate was then manually unlocked and rapidly opened. The bore then advanced over the false floor and finally over the sediment bed section, while all measuring instruments were recording. The opening time of the gate was recorded to calculate the non-dimensional removal period $t\,(g/h)^{1/2}$ .The expression should be less than the square root of two to achieve the ideal dam-break condition (Lauber and Hager, 1997). To investigate the effect of bed condition on bore velocity and scour depth, two initial conditions (wet versus dry conditions) were considered downstream of the gate. A schematic illustration of the experiment is presented in Figure 3, where h_u and h_d are the initial water depths (m) upstream and downstream of the gate, respectively. All the tests were conducted with an initial impoundment depth of h_u = 0.25 m, while downstream water depth h_d varied between tests (0 m, 0.025 m, 0.05 m, or 0.125 m). Since the impoundment water depths were kept constant, tests are named according to downstream water depths as dry bed, 0.025 m wet bed, 0.05 m wet bed and 0.125 m wet bed, respectively. For the experiment, a 1:40 Froude scaling ratio was used, resulting in h_u = 0.25 m corresponding to a prototype height of 10 m.

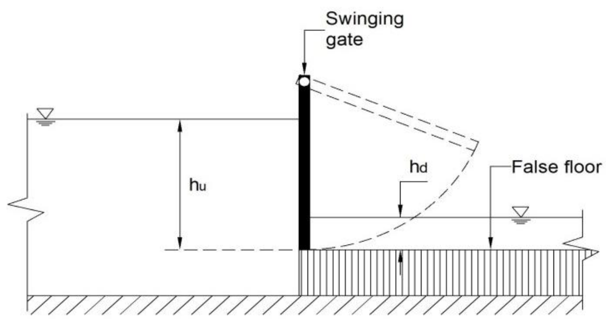


Figure 3: schematic illustration of the experiment

3 VALIDATION OF THE MODEL

A comparison between a dam-break analytical solution and the experimentally obtained bore profile is presented here. Because of the limited number of wave gauges, a number of identical tests were repeated with the same experimental configuration by installing wave gauges in sequential steps of 1 m to cover the entire flume. Repeated tests performed with the wave gauges at the same location showed a high degree of reproducibility in terms of wave arrival time and evolution of water depth. Figure 4 presents the comparison between the dam-break analytical solution and the experimentally obtained bore profile on the fixed floor before arrival of the bore on the sediment section. The x-axis corresponds to the direction along the flume length and h represents the water surface elevation. Chanson's (2006) solution considers the bottom friction in the dominant wave tip region, using the diffusive wave equation and Darcy-Weisbach friction factor (*f*). The value of *f* was taken as 0.03, described as a smooth surface. As shown in Figure 4, a good agreement can be observed between the experimental bore profiles and Chanson's solution.

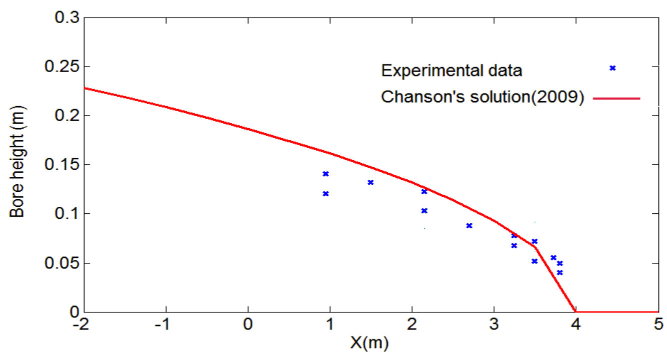


Figure 4: Comparison between dam-break analytical solution and the experimentally obtained bore profile for h_u = 0.25 m, h_d = 0 m at t = 2.48 sec

4 RESULT AND DISCUSSION

4.1 Scour mechanism

Figure 5 shows the measured results for the initial condition of h_u = 25 cm and h_d = 0 cm (dry bed condition). The black line represents the horizontal velocity measured 50cm upstream of the structure. The green and red lines show the scour depth and water surface elevation time-histories, respectively, measured at the front face of the structure. It can be seen that stream-wise velocities were captured after 2 s. The ADV measurements were noisy for the first 2 seconds of advancing bore as a result of air bubble entrainment and cavitation during the first few seconds after the bore arrival. The graph shows that significant scour depth occurs over a short period of time after the initial impact of the bore.

The short duration and turbulent nature of the bore induced a rapid scouring process. The initial bore front had a vertical front profile, and the maximum bore depth was attained within 8 seconds. The maximum scour depth occurred 13 seconds after the arrival of the bore front.

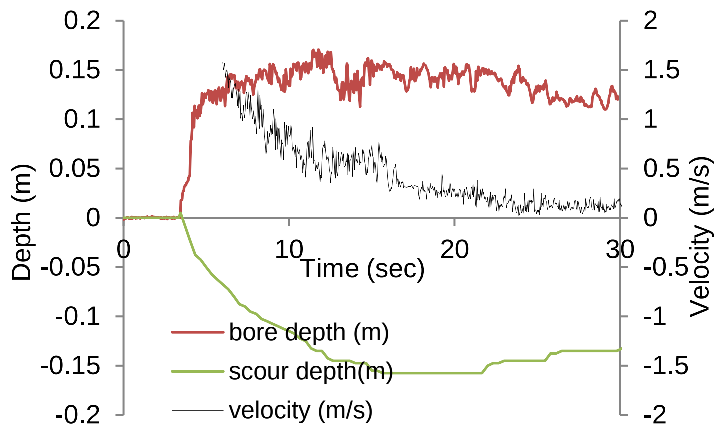


Figure 5: Water surface elevation (red line) and scour depth time history (green line) measured at the front face of the structure and horizontal velocity (black line) measured 50cm upstream of the structure for $h_u = 0.25$ m, $h_d = 0$ m

The critical shear stress for initiation of sediment motion was calculated from the Shields diagram in order to compute critical shear velocity. For the 1 mm grain size, the calculated critical velocity was 0.28 m/s. Figure 5 shows that the highest scour rate coincided with the largest flow velocities greater than the critical velocity. As the flow velocity decreased, the scouring pace slowed and the suspended sediment started to settle, filling the scour hole.

4.2 Effect of bed condition

Generally, the first tsunami wave propagates in a form of turbulent hydraulic bore over coastal areas that are in a dry bed condition, while the second or third tsunami waves may advance into the previously inundated inland area, which is referred to as the “wet bed condition”. It is reported that the presence of a still water layer (h_d) can significantly influence the bore propagation characteristics. In this section, the bore propagation characteristics and the resulting scour profile on both wet and dry bed conditions are compared and discussed.

4.2.1 Bore front velocity (U)

Figure 6 presents bore front average velocity as it propagated to the downstream end of the flume. The propagation of the bore front along the flume was tracked using the high-speed video camera. The velocity was calculated using the time sequence of the video recordings and the distance between the two gridlines. This velocity was assumed to represent the average velocity for that section. In general, for both fixed and movable beds, the highest velocities were recorded at locations closest to the gate, as a result of the bed friction. The bore front velocity gradually decreased as the bore propagated to the downstream end of the flume.

On the fixed bed, maximum instantaneous velocities reached as high as 2.26 m/s for the dry bed. The bore front velocities were 2.15 m/s, 1.84 m/s and 1.75 m/s for the 0.025 m wet bed, 0.05 m wet bed and 0.125 m wet bed, respectively. The bore front velocity decreased as the downstream water depth increased. The presence of the still water layer caused a resistance to the propagation of the incoming bore, inducing energy dissipation in the bore front. The higher downstream water depth resulted in lower total head and subsequent less kinetic energy and lower velocity. Therefore, the fastest bore front velocity occurred in the dry bed condition.

Conversely, the velocity measurement on the mobile bed showed different trends from that of a fixed bed. The bore front velocity in wet bed conditions with a thin layer of water was faster than observed in dry permeable bed. This was likely a result of water infiltrating into the bed under the dry condition, given the porosity and permeability of the sediment bed. In other words, energy dissipation due to seepage is presumed to originate from the interface between the fluid and the sediment bed. This counters some previous results in other studies discussed in Section 1. Chanson (2003) and Stansby et al (1998) observed that the speed of the bore on a dry (fixed) bed is higher than that on a wet bed. However, for both of their experimental conditions, the bed was solid and hydraulically smooth, with no sediment (zero porosity). Therefore, the present results indicate that the conclusion of higher bore front velocity moving over a dry fixed bed cannot be expanded to the case with a sediment bed.

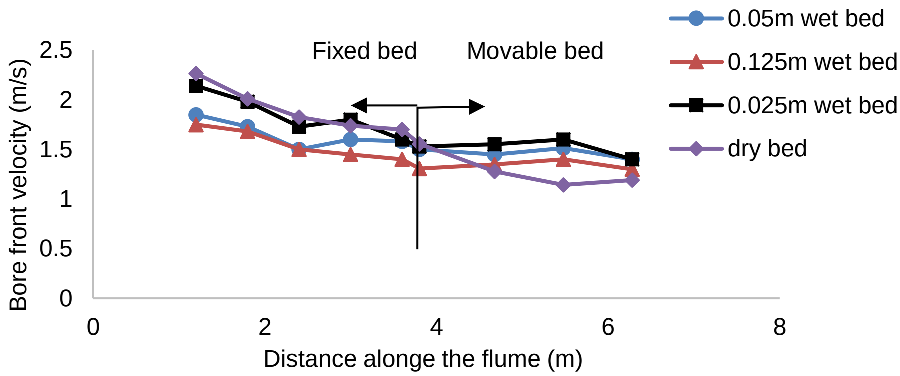


Figure 6: Bore front velocity along the flume for all initial conditions

4.2.2 Run up and stream-wise velocity of bore propagation

Comparisons of the time-history of water surface elevation at the upstream face of the structure and stream-wise velocity are shown for different initial conditions in Figure 7. It can be seen that the run-up height resulting from the initial impact was influenced by the bed condition. The run-up height reached the highest elevation (0.175 m) for the case of bore propagating over a thin layer of water (h_d =0. 025 m). The maximum run up heights were 0.17 m, 0.15 m and 0.11 m for h_d =0 m, h_d =0.05 m and h_d =0.125 m, respectively. Therefore, it can be seen that splash height in wet bed condition with thin layer of water was slightly greater than that of the dry bed condition.
Comparing the results in wet bed condition, a consistent reduction in the run up height was observed with increasing downstream water depths. The maximum run up height for the dry condition was 0.17 m, which occurred 7.9 s after the arrival of the bore front; while maximum bore depth was attained within less than a second for wet bed conditions. This also contrasted other studies, such as Stansby et al (1998) and Douglas and Nistor (2014), which observed that maximum bore heights occurred within 0.5 s after the initial impact for bores propagating over dry smooth solid beds. This delay in maximum run up height again could be caused by permeability of the mobile bed under dry conditions. Moreover, a delay in the arrival of the bore front was observed as the downstream depth increased, which shows a similar trend as the bore front velocity. For the wet bed conditions, a relatively vertical bore front was measured with respect to the dry bed condition. Observations showed steeper and deeper bore front with higher air entrainment in the bore front for wet bed conditions as the downstream water depth increased. To further analyze the effects of bed condition on propagation characteristics, a time-history of stream-wise velocity, measured upstream of the structure, is also given in Figure 7 for all initial downstream water depths. In all cases, the ADV sample volume was set such that it would be at or just below the bore water surface. As noted above, the stream-wise velocity measurements began 2 s after arrival of the bore. According to Figure 6, the bore front velocities at the location of the model structure were 1.14 m/s, 1.6 m/s, 1.51 m/s and 1.4 m/s, while from Figure 7 the maximum stream-wise velocities were 1.57 m/s,1.45m/s, 1.005 m/s and 0.554 for h_d=0 m, h_d=0.025 m, h_d=0.05 m and h_d=0.125 m, respectively. It appears that the lowest bore front velocity occurred in the dry bed condition, whereas the dry bed run had the highest measured stream-wise velocity 2.53 seconds after bore arrival. It appears that saturation of the initially dry bed allowed for increased velocity following passage of the bore front. Moreover, these results show reductions in the stream-wise velocity for increasing initial downstream depths, similar to the trend for bore front velocity.

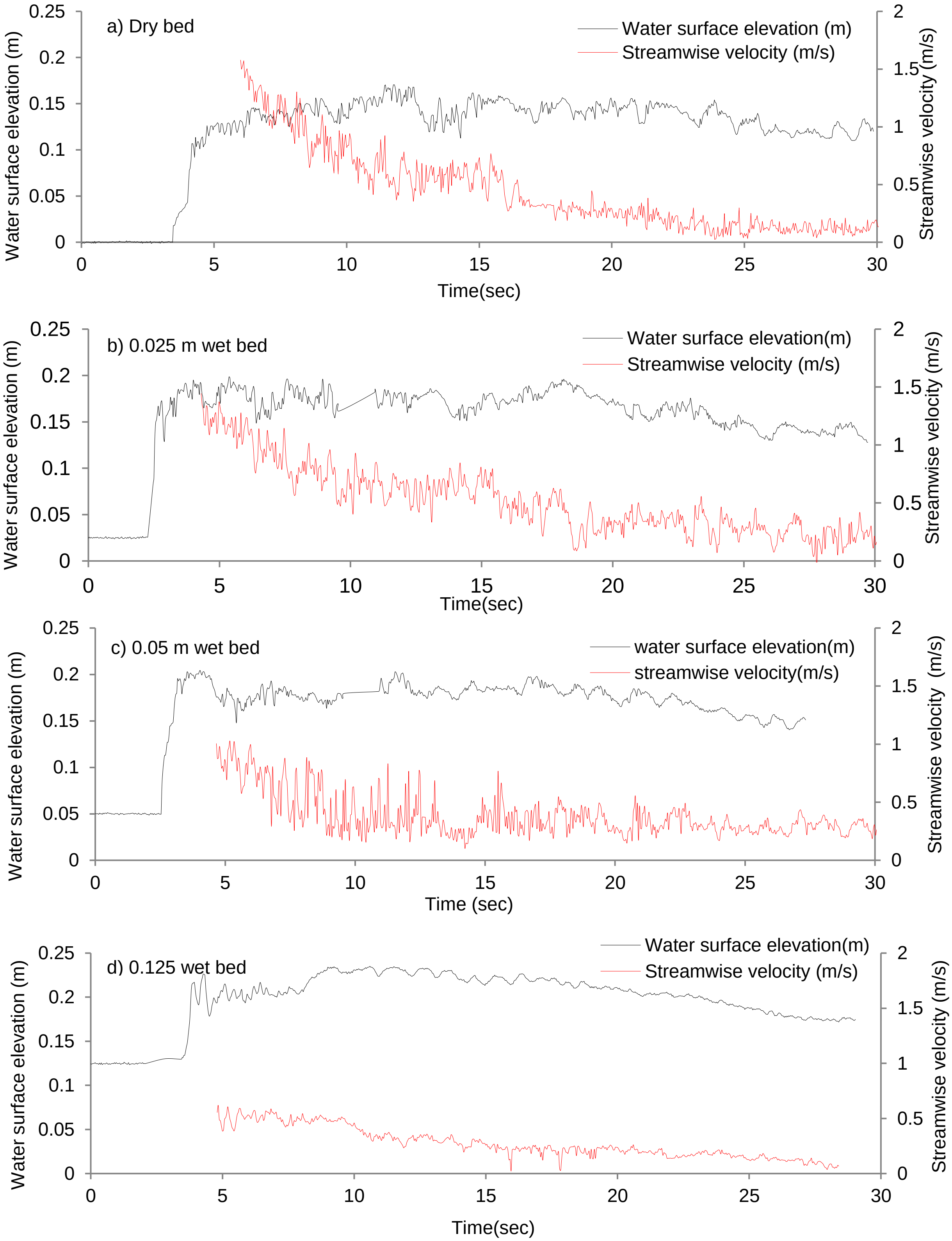


Figure 7: measured water surface elevation (black line) and measured streamwise velocity (red line) for a) h_d = 0 m, b) h_d = 0.025 m , c) h_d= 0.05 m and d) h_d = 0.125 m

4.2.3 Scour depth

Figure 8 demonstrates time-history of scour depth for all the experimental tests. For better comparison of all the tests, time zero refers to the bore arrival time at the structure, i.e., when the scouring process would be initiated. The magnitude of the scour depth for the 0.025 m wet bed was 0.16 m, which was slightly larger than that generated for the dry bed test (0.15 m scour depth). This would imply that the second tsunami wave can be even more destructive than the first wave propagating on dry land. The scour depths were respectively 0.12 m and 0.03 m for the 5 cm and 12.5 initial water depths, reductions of 40% and 140% compared to the 2.5 cm initial water depth case. Therefore, similar to bore front velocity and stream-wise velocity, a substantial reduction in scour depth was observed with increasing the downstream initial water depth. The presence of the initial still water depth weakened strength of the down-flow at the structure face and the bore became less effective at displacing the sediment grains around the structure. In contrast, Arneson et al (2012) reported that the scour capacity of a steady flow field reduces as the flow depth decreases. The down-flow at the pier face becomes less well developed because it has a shortened length over which to develop. The vorticity of the horseshoe vortex weakens as the down-flow weakens, and the wake vortex also weakens due to the increased importance of bed friction in a shallower depth. There is a noticeable difference between the time that it takes for the maximum scour depth to form in a dry bed compared to that of wet bed conditions The maximum scour depth in the dry bed condition was attained 14 s following the bore arrival, while for the wet bed tests it was attained within 7, 7 and 4.6 s. This was likely because under the dry bed condition the bore reached the structure before the bed was saturated completely.
Lastly, it can be seen that the final scour depth was less than the maximum scour depth. Therefore, using the observed final scour depth as a design criterion for the foundation of coastal structures is not recommended.

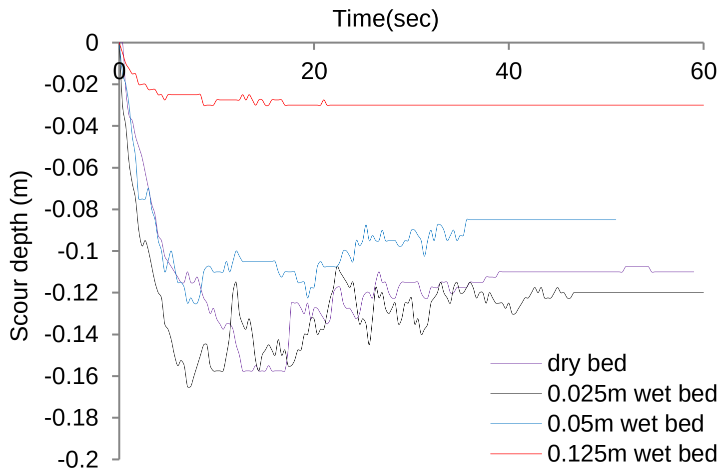


Figure 8: scour depth time history for different downstream initial conditions

5 CONCLUSIONS

In this study, the scouring mechanism around a square structure due to a tsunami-like, inland propagating bore and the influence of bed condition (dry vs wet) and (fixed vs movable bed) on bore characteristics and the resulting scour has been investigated experimentally. Based on the analysis of the recorded data, the following conclusions have been drawn:

- The short duration and very turbulent nature of the bores induced a rapid scouring process. Significant scour depths were reached over a short period of time at the front of the structure.
- The importance of the downstream depth on bore development and its propagation characteristics is shown. The existence of the still water layer caused a resistance to the propagation of the incoming bore and resulted in energy dissipation of the bore front.

- The present results indicate that the previous observation of higher bore front velocity moving over a dry fixed bed cannot be expanded to sediment bed cases. As a result of water infiltrating into the bed, the bore front velocity was less for the dry permeable bed case than wet bed cases with downstream water depth.
- Similar to bore front velocity and stream-wise velocity, a substantial reduction in scour depth was observed with increasing downstream initial water depth.

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